Transition to the region of central collisions and critical phenomena

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Abstract

The experimental results on the relation between the processes of total disintegration of nuclei (or the cases with central collisions) and the critical phenomena which can occur in the region of high degree of nuclear disintegration or of collision centrality are discussed.

1 Analysis of the events characteristics depending on disintegration degree of nuclei.

We want to note that to determine the disintegration degree of nuclei or the centrality degree of collisions the following variables are usually used : n_p - number of protons, n_f - number of fragments, E_{ZD} - the energy flow of secondary particles at an emission angle $\theta = 0^0$ and E_t - the transverse energy of secondary particles.

The research of the processes with total disintegration of nuclei (TDN) was started long ago in the experiments with emulsion nuclei [2]. In these experiments to select the events with TDN the condition $N_h \geq 28$ is used. In fig.1 the typical event of the processes of TDN in $p + Em$ (reactions at the momentum of 70 GeV/c) is shown. It was found in 1976. 66 h - particles and 22 s -particles were identified among the final reaction products. Particular analysis have demonstrated, that there are 57 one-charge particles ($Z = 1$) ,5 two-charge particles ($Z = 2$) and 4 particles with $Z \geq 3$, among h - particles. Respectively summary charges of h - particles in this case is the $Z \geq 79$ at insignificant remainder mass. Thus the TDN took place here.

Here we want to remind that the interest in the processes of TDN was primarily connected with the assumption that high densities of nuclear matter could be realized in these processes and the effects, related to collective properties of nuclear matter, c ould be observed. However, contrary to the expectations, one could not receive in the experiment an unequivocal answer to the question on the realization of these states.

To our opinion, such situation is mainly connected with some methodical difficulties that in the emulsion experiments there was no opportunity to take into account the cases, in which large momentum were transferred to fragments in interactions; the energ y characteristics of secondary particles were not practically determined, and the statistical material, as a rule, did not exceed some hundred events.

Taking into account all this and also the importance of the problem, the processes with TDN were studied in our experiment [3] according to a new experimental statement. It included the following:

(a) expansion of methodical opportunities of the experiment. As the bubble chamber technique was used, we had an opportunity to determine the energy and charge of all secondary particles.

(b) development of new selection criteria of events with TDN. For this purpose, the idea is used that the processes with TDN correspond to qualitatively new states of nuclear matter and the transition to these states occurs in nuclear interactions when the number of protons emitted from nuclei, Q , reaches a critical value of Q^*. Consequently the presence of Q^* must point to the existence of regime change in the behaviour of the characteristics of secondary particles in Q-dependences in the region close to Q^*. Hence one can use the following condition as a selection criterion for the events with TDN:

$Q \geq Q^*$.

This method of selection of the events with TDN is experimentally realized by studying the behaviour of different characteristics of secondary particles (a_i) in hadron-nuclear and nuclear - nuclear interactions depending on Q .

Here I want to discuss the results of paper [4] in which the experimental data on the Q-dependences of the values of single-particle two-dimensional correlation functions R are presented. The values of Q were determined as

$Q = N_+ - N_{\pi^-}$

here N_+ and N_{π^-} are the numbers of positively charged particles and π^-– mesons , respectively . In such determination Q is a sum charge of an event. We analyse the

$R(x,z) = \frac{\frac{d^2N}{dxdy}}{\frac{dN}{dxdy}} - 1$

function. The values of $R(x,z)$ were normalized in such way that the values of $R = \pm 1$ in the cases of maximum correlation and $R = 0$ in the cases when the correlation is absent. Here $+1$ corresponds to positive correlation and -1 to negative one .

The experimental data have been obtained from the 2-m propane bubble chamber of LHE, JINR . In this experiment, we used 5284 pC-, 6735 dC- , 4852 ^4HeC- and 7327 ^{12}CC-interactions at the momentum of 4.2 A GeV/c (the methodical d etails are described in [8]) . The statistical material was divided into the groups of events with the following values of Q:

$Q \geq 1; 2; 3; ...$

The values of R function were determined for π^-– mesons and protons. We have considered the following correlation functions $R(p,\theta), R(p,p_t), R(p,y), R(p,\beta^0), R(\theta,p_t)$, $R(\theta,y), R(\theta,\beta^0), R(p_t,y), R(p_t,\beta^0), R(y,\beta^0)$, here :

- p is 3-momentum in the laboratory coordinate system (lcs);
- θ - emitted angles in the lcs;
- p_t - transverse momentum;
- y - rapidity in the lcs;
- β^0 - order of cumulative (here $\beta^0 = (E - p_L)/m_N$, E is the total energy (in the lcs), p_L is the longitudinal momentum (in the lcs) and m_N is the nucleon mass).

According to the character of the Q - dependence of R functions , the data can be divided into two groups : group I - the data on the Q independence of R and group II - the data showing the Q-dependence of R . We shall not discuss the r esults of the first group.

We obtained the following result that in 90 % cases of group II the Q-dependence of R- function connected with the variable p_t.

The absolute values of R- function depending on Q for group II are shown in figures 2-5, the curves are hand drawn). We present the data which point to the regime changes in Q-dependences of $|R|$. The obtained results showd that in 75% ca ses , the Q-dependence of R has a nonlinear character , i.e. the regime changes take place. These data allows to determine the " critical" values of $Q = Q^*$ corresponding to the transition from one region to another.

Thus , we have that the correlation analysis confirm that the events with TDN qualitatively differ from "usual" events, and it could use the condition

$Q \geq Q^*$

for their separation.

From the figures we can also obtained the following results:

- in 82 % of cases for group II the R function has the values $R < 0.3$, i.e. weak correlations take place ;

- the correlations weaken with the increasing of A_p;

- the character of the Q - dependence of $|R|$ also changes with the increasing of A_p in the region of high Q (the region of TDN). This dependence has a form of line with a "break" for pC-, dC- interactions, it the step-b y step form for ^4HeC interactions and a "zigzag" form for ^{12}CC–interactions. It is possible that the "zigzag" form is the result of the influence of nuclear fragments, as the number of the fragments is the most in the ^{12}CC–interac tions.

Thus the results, obtained in this paper , have confirmed the assumption that there is a boundary value of Q^* for the quantity Q the existence of which leads to TDN. They also confirmed the idea that the processes with TDN correspond to qualit atively new states of nuclear matter and the transition to these states occurs in nuclear interactions when the number of protons emitted from the nuclei, Q , reaches a critical value of Q^*.

2 Processes of total disintegration of nuclei and the cases with central collisions.

Now I want to note that in paper [1] it was experimentally shown that the processes with TDN correspond to the central collisions (CC). The importance of these investigations is connected with the following. The search for signals from superdense st ates of nuclear matter is one of the basic trends of research in the experiments on relativistic nuclear physics [5]. The best conditions of such states research are the studies of the events with a maximum number of nucleons - participants in the inter action or events connected with CC of nuclei [6]. To select such events, the following criteria are usually used: events with a maximum number of secondary particles or events with a minimum flow of secondary particles energy emitted at a zero an gle. Theoretically, both of these conditions must correspond to the value of impact parameter $b - -- > 0$. The "centrality" of nucleus - nucleus collisions is really a necessary condition for arising the superdense states of nuclear matter. However, thi s condition cannot be sufficient as there are processes which are also characterized by a high degree of CC but do not result in arising superdense states of nuclear matter . In these cases, it is necessary to introduce an additional condition of selecti on of events to observe a signal from superdense states of nuclear matter. We think that such conditions can be obtained from the research of processes with TDN [7]. For this purpose, first of all, it is necessary to relate processes with TDN to cases wi th CC.

We used the experimental data on the $pC, dC, ^4HeC$ and ^{12}CC interactions at the momentum of 4.2 A GeV/c obtained from the 2-m propane bubble chamber.

The total statistics of the events are:

- 8130 events - pC ;
- 6945 - dC ;
- 11248 - ^4HeC and
- 20407 - ^{12}CC .

Methodical details are described in paper [8].

To relate events with TDN to the cases with CC, it was supposed that if these events correlated then with the increasing of the disintegration degree of nuclei - Q the average values of the variable K must decrease and reach a minimum value. The va lues of K are determined in the following way:

$$K = \frac{\sum_{i=1}^{n} p_i^2}{\sum_{i=j}^{N} p_j^2} \tag{1}$$

here p_i^2 is the 3-momentum square of an i-th charged particle with an emission angle $\theta < 5$ and n is the number of these particles; p_j^2 and N are respectively the 3-momentam squared of a j -th charged particle and the number of all c harged particles in the event. Q was determined as $Q = N + -N_{\pi^-}$.

I want to note that the average values of impact parameter $< b >$ must also decrease with the increase of Q if the condition of CC, corresponding to the minimum values of b ,is really achievable. To determine the values of $< b >$, we used th e calculated data on quark-gluon string model[13]

Fig. 6 shows the Q-dependences of the average values of K. It is seen that the values of $< K >$ decreasing with the increase of Q : for ^{12}CC interactions in the interval $Q \geq 6$, for $^4HeC - -Q \geq 4$, and for dC, pC - in teractions in the interval $Q \geq 3$.

Thus, one can conclude that in the interval of high Q , i.e. in the area of TDN, the average values of K decreas with the increase of Q and reach their minimum at the maximum value of Q . From here it follows that the events with TDN corresp ond to the cases with a minimum flow of energy of charged particles at an emission angle of $\theta < 5^0$.

One can also see (fig.7) that with the increasing of Q , the average values of b decreas and reaches its minimum at a maximum value of Q . This means that the processes with TDN, in the framework of a quark-gluon string model, correspond to e vents with the highest CC.

3 Critical phenomenon.

To further confirm the result of the existance of the points of the regime changes on the behaviour of some characteristics of secondary particles ai depending on Q I want to say that at present there are many theoretical papers in which the proc esses of nuclear fragmentation [9] and the processes of TDN [10] are considered as a critical phenomenon. Therefore it is possible to suppose that if there exist cases corresponding to the critical phenomena among the events with the TDN then the po ints of the regime changes in the behaviour of some characteristics of secondary particles depending on the disintegration degree of collisions - Q could be observed. And I want to add that there are the experimental data obtained in the proton - n uclear and nuclear-nuclear interactions at high

energy demonstrate the existence of the points of the regime changes in the behaviour of the $a_i = f(Q)$ distributions.

For example in fig. 8 the average multiplicity of relativistic charged particles depending on Q is shown for the $^{28}Si_{14}+Em$- reactions at the energies 3.7 and 14.6 GeV per nucleon. To determine the Q a number of charged projectile fragm ents (Z_f) were used. The figures were obtained from paper [11]. The points of the regime change are observed in these dependences. These points were used by authors to select the events with CC of nuclei.

In fig. 9 there are shown the average values of pseudorapidity $-\eta = -lntg(\theta/2)$ for s-particles(the particles with $\beta > 0.7$) depending on the number of g-particles(the particles with ($\beta 0.7$) for pEm-reactions at the mo menta of p_0=4.5; 24.0;50.0;67.0 and 200.0 GeV/c. This figure was obtained from paper [12]. The dashed line in the figure corresponds to the cascade-evaporation model calculations. The points of the regime changes in these distributions are also seen. The cascade-evaporation model calculations cannot describe numerically these distributions.

In fig. 10 there are shown the E_t-dependences of the relations of cross sections for the J/ψ- production and Drell-Yan processes at the SPS energy (158 GeV per nucleon) for $Pb + Pb$ reactions(the results of NA50 Collaboration). The full line c orresponds to the interactions of light nuclei. The points of the regime changes in these figures are also seen.

Thus the results clearly demonstrate that there exit the points of the regime change of the behavior of $a_i = f(Q)$ distribution which could fix the region of the TDN. As I have noted at present there are many papers in which the processes of nucle ar fragmentation and the processes of the TDN are considered as the critical phenomena and for their description a percolation approach was proposed. We therefore want to use the percolation approaches that as statistical and percolation theories can d escribe the critical phenomena best of all. But the discussed data showd that the points of the regime changes were also observed for interactions of the light nuclei in which the conditions for applying of statistical theories are practically ab sent. Supposing these points being connected with the appearance of a critical phenomenon the fragment number change could also have a critical character with the Q increase, because the intermediate nuclear formations (for example percolation cluster) could be a source of the nuclear fragmentation.

To experimentally test this idea we used the experimental data obtained from the 2-m propane bubble chamber of LHE, JINR. We used 20407 ^{12}CC- interactions at the momentum of 4.2 A GeV/c[8].

To reach the purpose we investigated a number of the events depending on the variable Q. To determine the values of Q two variants were considered. In the first variant the values of Q were determined as

$Q = n_{\pi^+} - n_{\pi^-} + N_p$,

here n_{π^+}, n_{π^-} and N_p are the number of identified π^+, π^- - mesons and protons respectively . In that determination Q is a number of all the protons in an event without taking into account a remainder of nuclei. In the second variant the values of Q were determined as

$Q = N_+ - n_{\pi^-}$,

here N_+ are charges of all the positively charged particles in an event including nuclear fragments. In that determination Q is a summary charge of an event.

The distributions of the events number depending on Q are shown in fig.11a,b. Here the empty starlets correspond to first variant of Q-determination, the full starlets - to

second ones (the cases in which the nuclear fragments were included). There are three regions in these dependences. They are shown by the full lines drawn by hand. The first region corresponds to the values of $Q \simeq 2$, it is usually named the region of peripheral collisions. The second region corresponds to the values of: $Q \simeq 3 - 7$. It is usually named the region of semicentral collisions. The third region corresponds to the values of $Q \simeq 8 - 12$. It is usually named the region of CC. It is also seen that with the enclusion of fragments number to determine Q the form of distributions sharply changes and has a two–steps structure(full starlets).

It is also seen that the fragments number to determine the Q being included the form of distributions sharply changes and has a two-steps structure(full starlets).

In fig.11b there are shown the Q-dependences of the events for the calculation data obtained from the quark-gluon string model [13] (QGSM) without nuclear fragments. The empty starlets correspond to the cases in which the stripping protons were not take n into account and the full starlets correspond to the cases in which the stripping protons were included. It is seen that the form of the distribution strongly differs from the experimental one in fig.11a. There is no two-steps structure in this figure. Therefore we can assert that this difference is connected with the existence of nuclear fragments in ^{12}CC- interactions.

Thus, the results demonstrate that the influence of the nuclear fragmentation process in the behaviour of number of the events depending on Q has a critical character. We suppose this result to be connected with percolation clusters.

To confirm the existence of the percolation cluster we analysed the angular spectrums - $N_i = f(cos\theta)$ of identified protons depending on Q and the number of fragments. The used distributions were normalaized on the total number of particles.

To investigate Q-dependences of N_i -functions we used the following quantities:
$f_1 = \frac{N_4 - N_3}{N_4 + N_3}$;
$f_2 = \frac{N_4 - N_2}{N_4 + N_2}$;
$f_3 = \frac{N_4 - N_1}{N_4 + N_1}$.

Here the N_1, N_2, N_3 and N_4 are the values of N_i the groups of the events with the values of $Q : Q \geq 5$ (this is peripheral collisions); $Q = 6-7; Q = 8-9$ and $Q \geq 10$ (this is CC) respectively. These quantities allow us to compare in deta il the angular distribution of protons from the events with different values of disintegration degree.

To investigate the values of f_i depending on the number of fragments we also used two variants to determine the variable Q.

Fig.12 shows the Q-dependences of f_1, f_2 and f_3 as a function of $cos\theta$. As well as in fig.11 the empty starlets correspond to the cases in which the nuclear fragments were not taken into account and the full starlets - to the cases in w hich the nuclear fragments were included. The difference between two determination of Q is observed only for the f_2 function i.e in the region of the fist step - the region of cluster formation.

Thus, the results demonstrate that the influence of nuclear fragmentation process in the behaviour of the events number and angular distribution depending on the Q have a critical character. To explain this result we suppose that it could be conne cted with the existence of percolation clusters. It is possible to think that with the increase of the centrality degree (fig. 13) the probability of cluster formation grows but further increase the Q (in the region of high Q) leads on the big clu sters decay to nuclear fragments and then on free nucleons. It could be a reason for observation of two-step structure in the distributions: the first step connected with the formation of percolation cluster and the

second one - with its decay.

4 Summary

1. The experimental results obtained in the proton- nuclear and nuclear-nuclear interactions at high energy clearly demonstrate the points of the regime change of the behaviour of some characteristics of secondary particles depending on the centralit y degree of collisions. It could mean that there are cases corresponding to the critical phenomena among the events with the central collisions of nuclei. We suppose that these points could be used to select the events with the central collisions of nuclei.

2. For ^{12}CC-interaction the behaviour of the number of events, depending on Q also depends on the number of fragments and has a two–steps form. This form is not reproduced by the calculated data in the framework of the QGS model which does n ot take into account nuclear fragments. This result as well as the results obtained from the analysis of angular distributions of protons in peripheral and central collisions could be a confirmation of the existence of percolation clusters.

Finally I want to say that at GSI, AGS and Nuclotron energies this result can signal of the existence of the transition of nuclear matter from nucleon states to its mixed ones. At SPS, RHIC or LHC energies , a similar result could help to detect "crit ical" signals of phasetransition nuclear matter.

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5 References

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6 Caption of figuers

Fig.1

Fig.2 Q-dependence of (R((,pt)(for (– mesons in pC , dC , 4HeC and 12CC interactions. The values of (R(shown at Q=1;2;3;... correspond to the groups of events with Q(1;2;3;... , respectively.

Fig.3 Q-dependence of (R(pt,y)(for (– mesons in pC , dC , 4HeC and 12CC interactions. The values of (R(shown at Q=1;2;3;... correspond to the groups of events with Q(1;2;3;... , respectively.

Fig.4 Q-dependence of (R(p,pt)(for protons in pC , dC , 4HeC and 12CC interactions. The values of (R(shown at Q=1;2;3;... correspond to the groups of events with Q(1;2;3;... , respectively.

Fig.5 Q-dependence of (R(pt,y)(for protons in pC , dC , 4HeC and 12CC interactions. The values of (R(shown at Q=1;2;3;... correspond to the groups of events with Q(1;2;3;... , respectively.

Fig.6 Q - dependence of the values of ¡ K ¿ for 12CC ,4HeC , dC and pC interactions.

Fig.7 Q - dependence of the values of ¡ b ¿ for 12CC ,4HeC , dC and pC interactions.

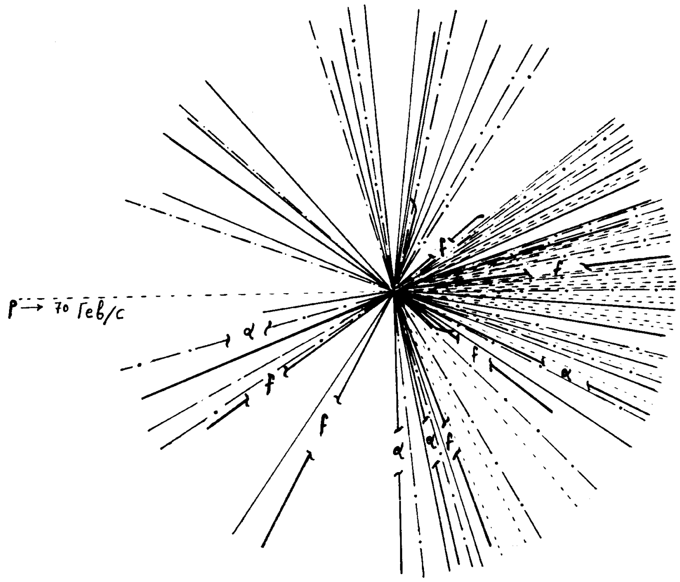
Fig.8

Fig.9

Fig.10

Fig.11a,b Q-dependence of the number of events.

Fig.12 Q-dependence of the angular distribution of protons.
Fig.13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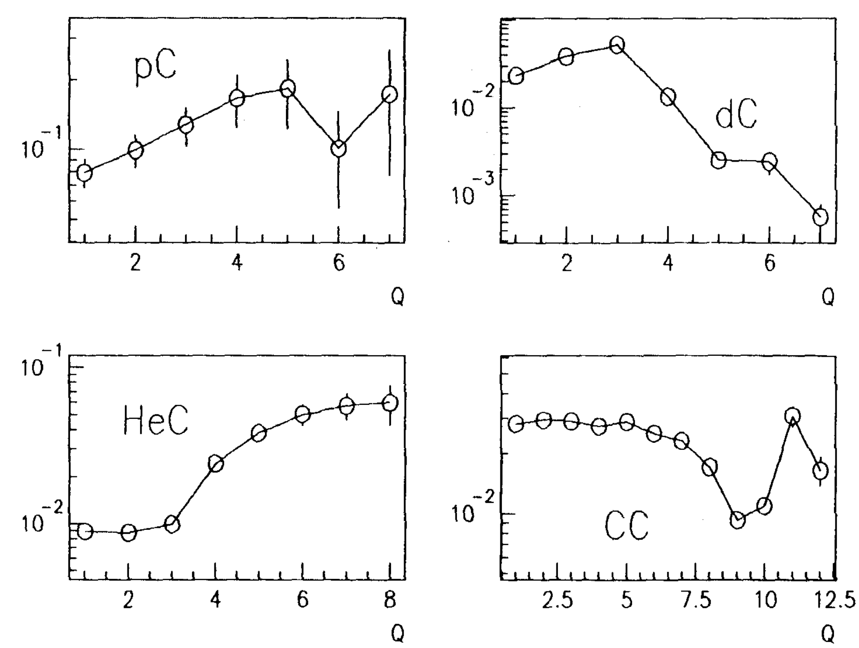
α
f
f
α
α f
f
α

Fig. 1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6
Q
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2
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6
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8
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10
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Q

Fig.2

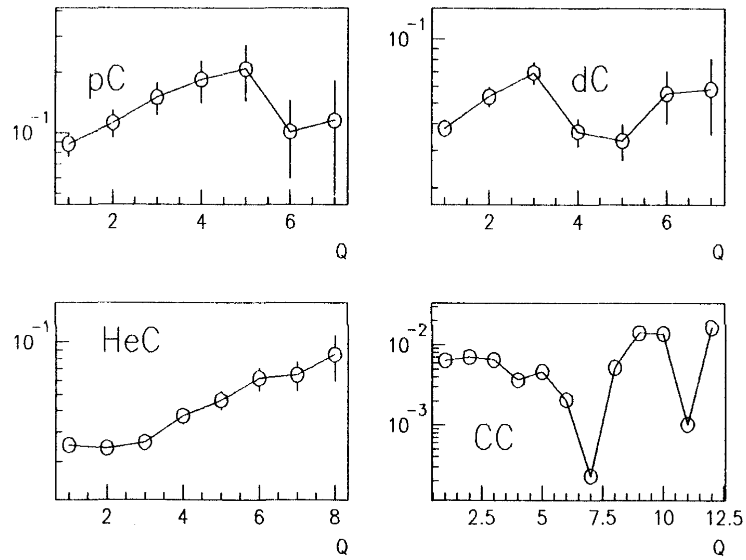


Fig.3

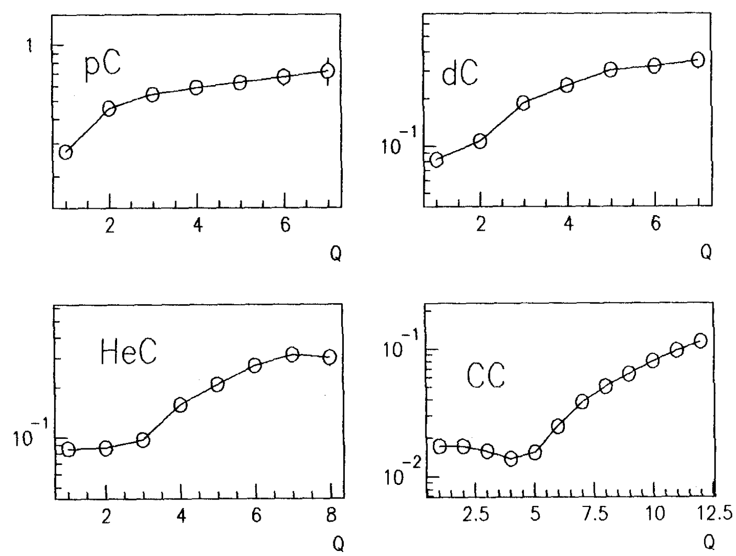


Fig. 4

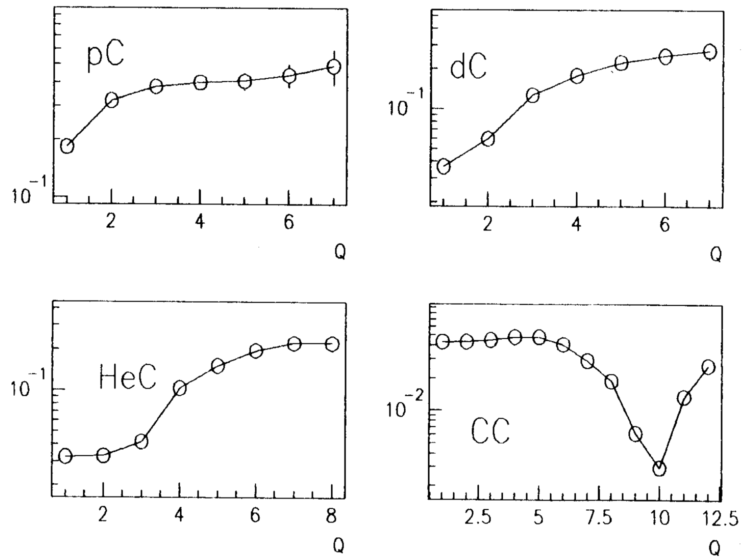


Fig.5

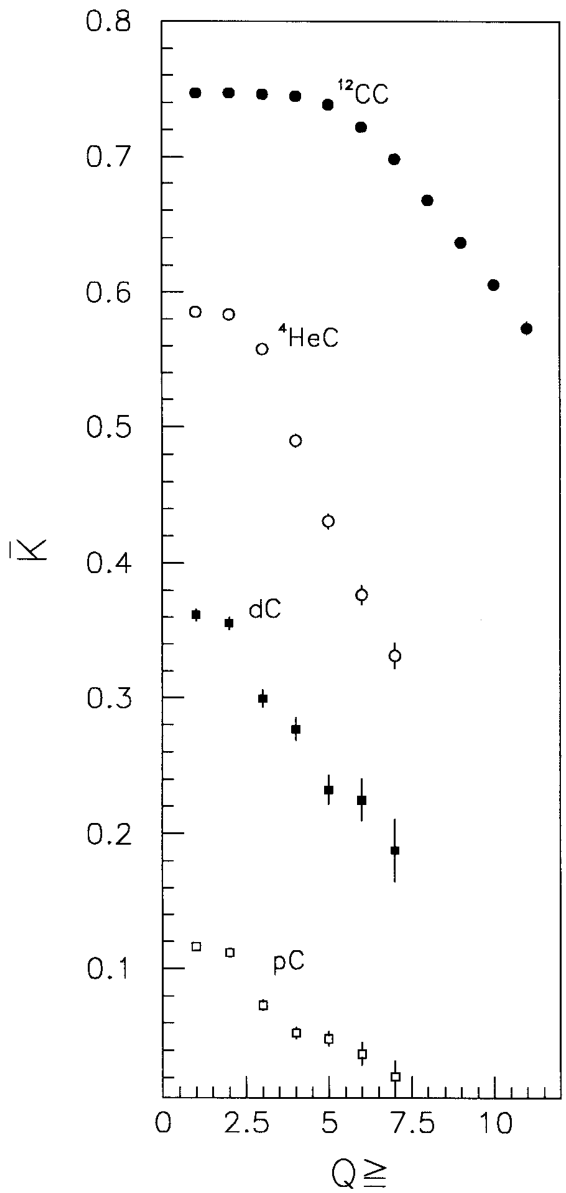


Fig.6

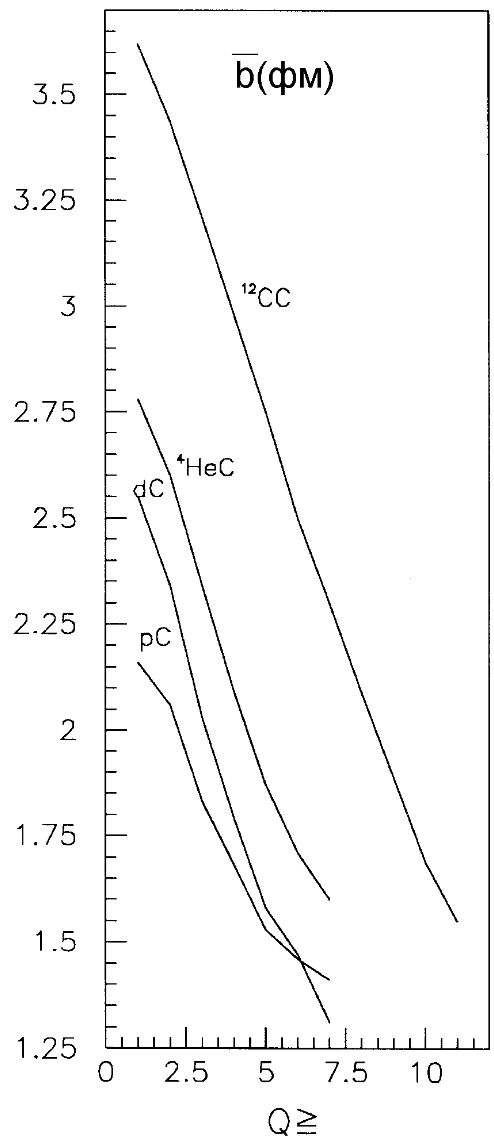
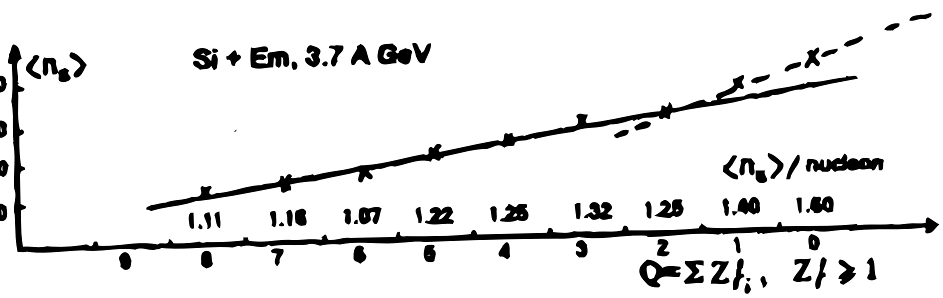


Fig.7

a)



b)

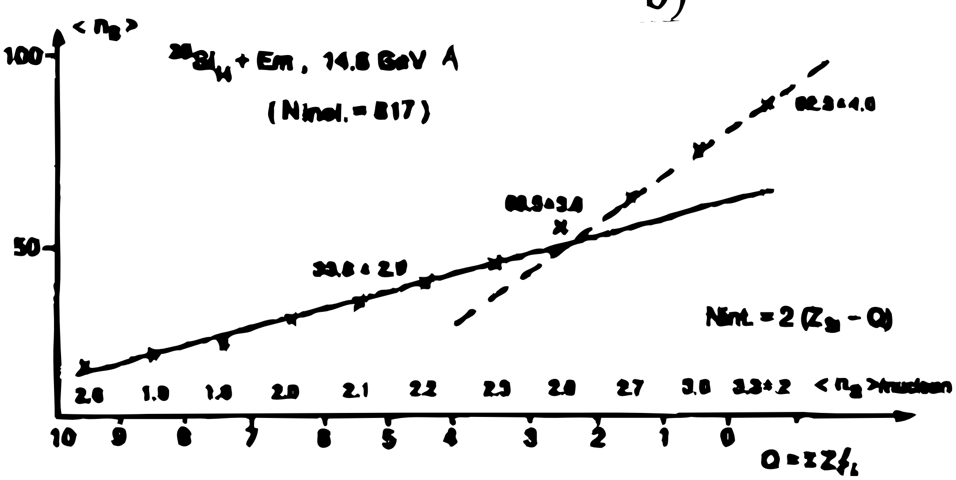


Fig. 1 a,b

Fig.8a,b

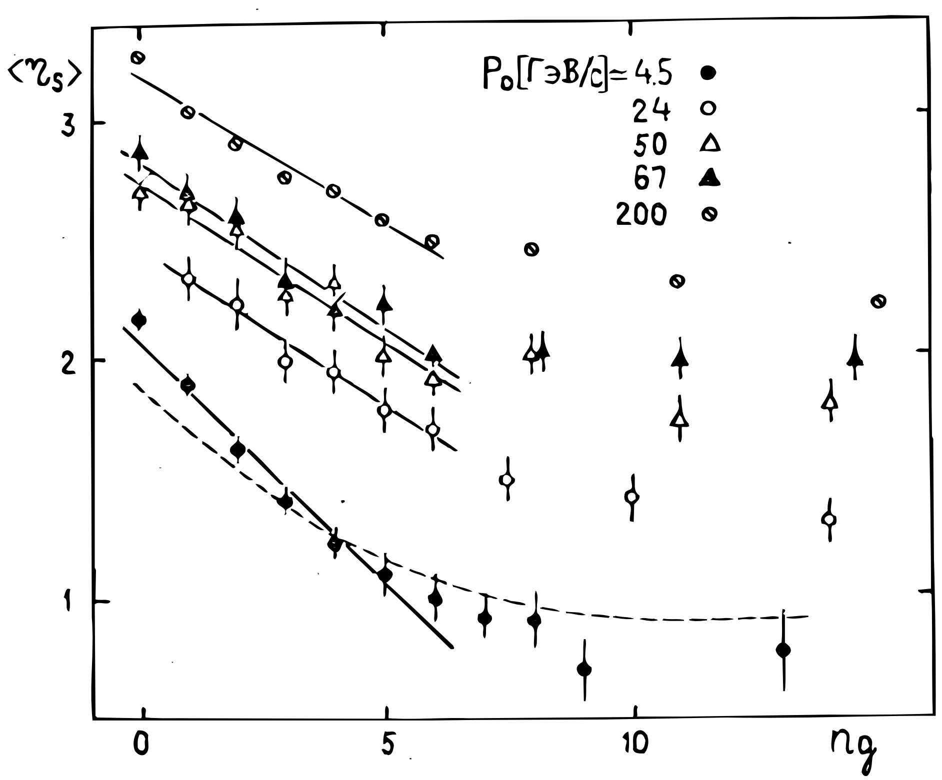
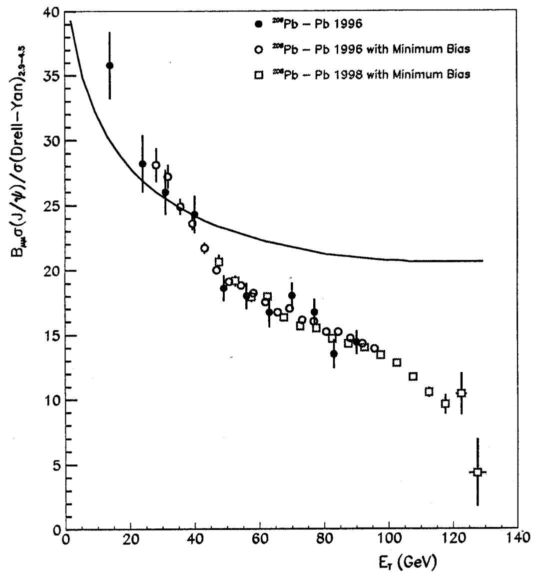


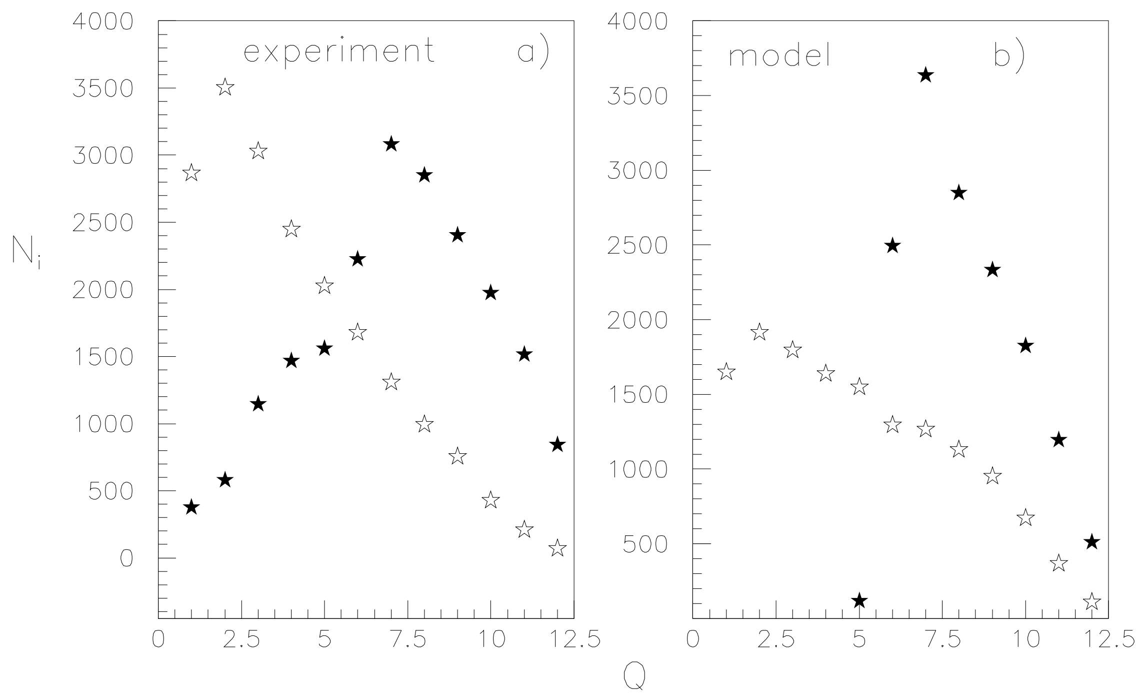
Fig. 2.

Fig.9



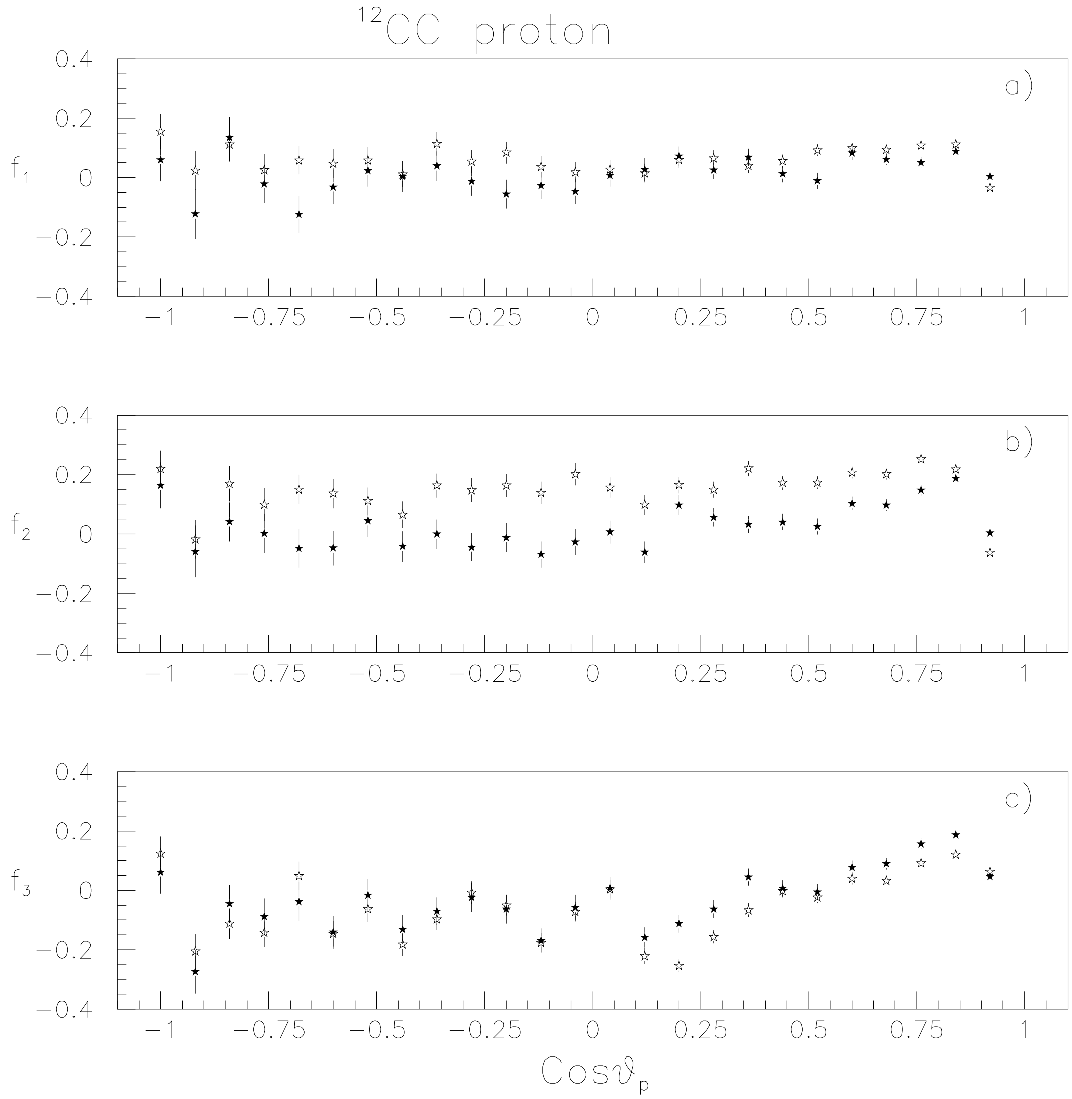
^{208}Pb – Pb 1996
^{208}Pb – Pb 1996 with Minimum Bias
^{208}Pb – Pb 1998 with Minimum Bias
$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
E_T (GeV)
0
5
10
15
20
25
30
35
40
20
40
60
80
100
120
140

Fig.12



experiment
a)
model
b)
N_i
Q
4000
3500
3000
2500
2000
1500
1000
500
0
0
2.5
5
7.5
10
12.5

Fig.11



^{12}CC proton
a)
b)
c)
f_1
f_2
f_3
0.4
0.2
0
−0.2
−0.4
−1
−0.75
−0.5
−0.25
0
0.25
0.5
0.75
1
Cosϑ_p

Fig.12

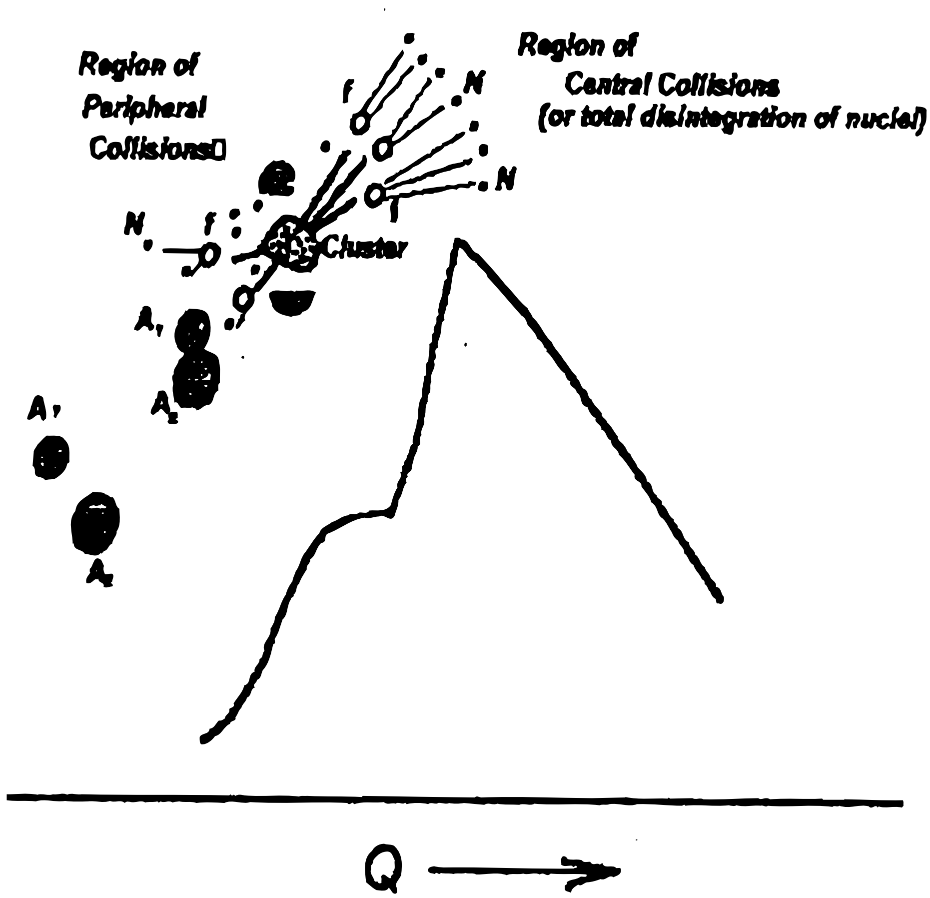

Region of
Peripheral
Collisions
Region of
Central Collisions
(or total disintegration of nuclei)
Cluster
Q

Fig.5

fig.13